A narrow line Seyfert 1–blazar composite nucleus in 2MASX J0324+3410

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ABSTRACT

We report the identification of 2MASX J032441.19+341045.9 (hereafter 2MASX J0324+3410) with an appealing object which shows the dual properties of both a narrow line Seyfert 1 galaxy (NLS1) and a blazar. Its optical spectrum, which has a $H\beta$ line width about 1600 km s^{-1} (FWHM), an [OIII] to $H\beta$ line ratio $\simeq 0.12$, and strong FeII emission, clearly fulfills the conventional definition of NLS1s. On the other hand, 2MASX J0324+3410 also exhibits some behavior which is characteristic of blazars, including a flat radio spectrum above 1 GHz, a compact core plus a one-sided jet structure on mas-scale at 8.4 GHz, highly variable fluxes in the radio, optical, and X-ray bands, and a possible detection of TeV γ-ray emission. On its optical image, obtained with the HST WFPC2, the active nucleus is displaced from the center of the host galaxy, which exhibits an apparent one-armed spiral structure extended to 16 kpc. The remarkable hybrid behavior of this object presents a challenge to current models of NLS1 galaxies and γ-ray blazars.

Subject headings: galaxies: active — galaxies: Seyfert – galaxies: peculiar – galaxies: jets – galaxies: individual (2MASX J0324+3410)

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1. Introduction

Since their identification as a special subgroup of broad line active galactic nuclei (AGNs), narrow line Seyfert 1 galaxies (NLS1s, Osterbrock & Pogge 1985) have drawn substantial attention in the AGN community over the last twenty years. The conventional definition of NLS1s consists of two criteria: 1) a narrow width of the broad Balmer emission line ($FWHM(H\beta) < 2\,000$ km s^{-1}); and 2) weak forbidden lines ($[OIII]\lambda5007/H\beta < 3$). Subsequent studies revealed their other unusual properties, such as 1) strong FeII multiplet emission (e.g., Boroson & Green 1992; Grupe et al. 1999; Veron et al. 2001; Zhou et al. 2006); 2) steep soft X-ray spectra (Wang et al. 1996; Boller et al. 1996; Grupe et al. 1998); 3) rapid and large amplitudes of X-ray variability (e.g., Leighly 1999; Komossa et al. 2000); and 4) commonly blue shifted UV line profiles (e.g., Leighly & Moore 2004). These unusual properties are in fact an extension to the extremity of a set of correlations between Hβ line width and the other observables. These correlations form the so-called eigenvector 1 (E1, Boroson & Green 1992; Sulentic et al. 2000). E1 is considered as the manifestation of the variation of one or a certain combination of several fundamental parameters of AGNs, such as the black hole mass and/or accretion rate.

NLS1s are usually radio-quiet (RQ) with radio loudness $R < 10$ (defined as radio to B-band optical flux ratio, $R \equiv f_{5GHz}/f_B$). The last decade has witnessed the identification of about two dozen radio-loud (RL) NLS1s (Grupe et al. 2000; Zhou & Wang 2002; Zhou et al. 2003; Zhou et al. 2005; Komossa et al. 2006a,b; Zhou et al. 2006). Given the intriguing fact that RL AGNs and "normal" NLS1s occupy the opposite extremes of the E1 parameter space (Boroson 2002), the study of RL NLS1s may provide important clues to understanding the physical drivers of E1.

First proposed by Spiegel in 1978 to refer to rapidly variable AGNs, blazars, including BL Lac objects and flat spectrum radio quasars (FSRQ), are another small distinct subset of AGNs. An operational definition is: flat radio spectrum above 1 GHz, fast variability, high and variable polarization, superluminal motion, and high brightness temperature (Urry & Padova 1995). Blazars are believed to be radio loud AGN viewed (almost) along the direction of their radio jets; so that non-thermal jet emission is relativistically boosted. In our recent work, we found that the two radio loudest NLS1s, SDSS J094857.3+002225 (Zhou et al. 2003) and 0846+51W1 (Zhou et al. 2005), both show blazar-like behavior. These results suggest that relativistic beaming may play an important role in very radio loud (VRL) NLS1s.

In this letter, we report the discovery of an appealing NLS1–blazar composite object, J032441.19+341045.9 (hereafter 2MASX J0324+3410), an extreme and the best example so far in the line of the NLS1-blazar connection. This object was first observed spectroscopically by Remillard et al. (1993) as an optical counterpart of an X-ray source detected in the HEAO-

1 X-ray survey, and was classified as a Seyfert 1 galaxy. It was subsequently observed by Marchã et al. (1996) but was (mis-)classified as a narrow line radio galaxy (NLRG). Here we present our new spectroscopic observation and classification, along with its broad band property; we defer to a future paper for detailed analyses of its full data set from both archives and our on-going monitoring observations. Throughout this paper, we assume a cosmology with H_0= 70 km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Observations, data analysis, and broad band properties

2.1. Optical Spectroscopy and NLS1 classification

We took spectra of 2MASX J0324+3410 with the OMR spectrograph attached to the Cassegrain focus of the 2.16m telescope at Xinglong Station of National Astronomical Observatory of China (NAOC) on Nov 25, 2005. A 1200 line mm^{-1} grating (50 Å mm^{-1} dispersion) and a Tek 1300 × 1024 CCD were used to cover a wavelength range of 1200 Å centered at 5100 Å. Four exposures of 60 minutes each were taken. KPNO standard stars were observed for absolute flux calibration. A slit width of 2.″5 was chosen to match the seeing disk. The spectral resolution as measured from the night-sky lines was 2.75Å at FWHM. The CCD reduction, including bias subtraction, flat-field correction, and cosmic-ray removal were accomplished following the standard procedures using IRAF. The spectra were extracted and combined into a 1-D spectrum with the Galactic extinction $E(B-V) = 0^m.213$ corrected.

We fit the spectrum with the following model components: 1) a power law continuum; 2) two Gaussians for the [OIII]$\lambda\lambda$4959, 5007 doublet; 3) two Lorentzians for Hβ and Hγ, respectively; and 4) the optical FeII multiplets of Véron-Cetty et al. (2004). The redshifts and profiles of the [OIII] doublet are taken to be the same, and their flux ratio is fixed to the theoretical value. We also assume that the broad component of Hβ, Hγ, and the FeII multiplets have the same redshifts and line profiles; and the same assumption is for the narrow component of these lines[1]. The result is displayed in Figure 1. We also tried to fit the broad component of the Balmer lines with Gaussian, and found that they cannot be fitted with a single Gaussian but two Gaussians are needed. This latter model yields somewhat broader FWHM but similar line strength compared to the former Lorentzian model for both the FeII and Balmer lines.

The redshift of 2MASX J0324+3410 as determined from [OIII] is $z = 0.0629 \pm 0.0001$,

[1] Véron-Cetty's FeII model includes forbidden FeII lines.

consistent with that of the Balmer lines within the measurement uncertainties. The Balmer line width, FWHM = 1 520 km s^{-1} for a Lorentzian model and 1 650 km s^{-1} for a double Gaussian model (after correction for instrumental broadening), is narrower than that of normal Seyfert 1 galaxies and quasars, but typical of NLS1s. The line ratio $[OIII]\lambda5007/H\beta$ is $\simeq 0.12$ and is almost independent of the choice of the line profiles. This value indicates that the bulk of the Balmer emission lines do not originate from the narrow line region (NLR) and hence excludes the possibility that 2MASX J0324+3410 is a type 2 AGN, e.g. a NLRG, as was claimed in Marchã et al. (1996).

The optical FeII complexes are rather strong with $EW(FeII\lambda4570) \sim 130\AA$ and $R_{4570} \equiv FeII\lambda4570/H\beta \sim 2.0$, where the FeII blend is integrated from 4434 to 4684 Å for both broad and narrow components with larger EW(FeII) and R_{4570} for the Lorentzian model. Remillard et al. (1993) reported a $R_{4570} = 1.54$. In summary, our optical spectrum clearly shows that 2MASX J0324+3410 is a classic NLS1.

2.2. Broad Band Properties and SED

Radiation from 2MASX J0324+3410 was detected in a wide wavelength range across almost the whole electromagnetic spectrum, in the radio, infrared (IRAS and 2MASS), optical band (e.g., Swift UVOT), X-ray and possibly γ-ray bands. It is a strong radio source with a flux density 304−581 mJy at 5 GHz, and shows a flat radio spectrum up to at least 10 GHz and significant flux variations. Using simultaneous observations at 2.695, 4.75, and 10.55 GHz, Neumann et al. (1994) found a flat spectral index, $\alpha \simeq 0.1$, and detected polarization at the 3%, 5%, and 4% level, respectively. A factor of 1.3 variation (4σ level) in its 1.4 GHz flux on time-scales of ten years was found by comparing the Green Bank 1.4 GHz Northern Sky Survey (GBNSS, White & Becker 1992) and the NRAO VLA Sky Survey (Condon et al. 1998). Even larger amplitude variations (a factor of 1.6 and 1.9) on shorter time scales (3.5 and 3.3 yrs) were observed at 5 GHz (Neumann et al. 1994; Griffith et al. 1991; Laurent-Muehleisen et al. 1997). These variations are significant at the 3–6 σ level, and cannot be attributed to source contamination as the beam sizes for observations at the higher flux states are (fortunately) smaller than those at the lower states. Assuming the flux variability is intrinsic, we can derive a lower limit on the brightness temperature of 5×10^{11} K (c.f., Zhou et al. 2006). This value is an order of magnitude higher than the equipartition value $\sim 5 \times 10^{10}$ K (e.g., Readhead 1994) but close to the inverse Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969).

The source was also observed by the VLBA in the VLBA calibrator survey (VCS). High resolution images at 2.2 GHz and 8.4 GHz reveal a core and a weak extended south-west component 6.8 mas (8.2 pc) away from the core (Beasley et al. 2002). We have re-processed the VLBA data. The core is further resolved into a brightest component in the north-east and an extension towards the south-west, reminiscent of a core–jet structure. The brightest compact component has a deconvolved size of about 0.1 mas (0.12 pc) and a flux of 0.165 Jy at 8.4 GHz, leading to a brightness temperature of about 4×10^{11} K, consistent with the estimate from the variability analysis above. The south-west component has a steep radio spectrum and seems to have no proper motion ($< 0.05c$; Yuan W. et al. in preparation), and therefore is possibly a weak radio lobe.

The radio loudness of 2MASX J0324+3410 is estimated to be $R = f_{5GHz}/f_{\rm B} = 38 - 71$ using the HST magnitude and assuming $\alpha_{opt} = 0.5$ for the nucleus. If we adopt the swift UVOT B magnitude of B=16.11 mag, we obtain $R \simeq$89-151, after correction for Galactic extinction. Note that the Swift B magnitude may include some contamination of the galactic light (see last section), so there can be a significant variation between the Swift and HST observations. Since the 5 GHz radio emission is likely subject to substantial enhancement due to the Doppler beaming effect, we try to estimate its 'intrinsic radio loudness' using a low-frequency flux, which is thought to be less affected by Doppler boosting. Assuming typical spectral indices $\alpha_r = 0.7 - 1.0$ for the extended radio components, we find an 'intrinsic radio loudness' 4–25 from the radio flux 1.02 Jy at 151 MHz (Hales, Baldwin & Warner 1993). This puts 2MASX J0324+3410 in the class of radio intermediate quasars. Its radio power, at 178 MHz, $P_{178{\rm M}Hz} \lesssim 8\times10^{24}$ W Hz^{-1}, as interpolated from the one at 151 MHz, is below the dividing line separating the FR II and FR I types.

X-ray emission as well as hard X-ray (and perhaps even γ-ray) flares have been detected from 2MASX J0324+3410 by various instruments. For observations with ROSAT and Swift, we reduced the publicly available data to derive the X-ray spectra and fluxes; for the rest of the data sets (mainly sky monitor type instruments), we made use of the X-ray count rates provided as available from NED. Hard X-ray emission was detected with the HEDs (High Energy Detectors, 2.6–60 keV) on-board HEAO-1 at three epochs over a time span of one year, when it showed decreasing averaged count rates from 1.25 ± 0.39 cts s^{-1} to 0.01 ± 0.26 cts s^{-1}. It was also detected in the ROSAT All Sky Survey (RASS), with a 0.1–2.4 keV flux of $3.1\pm0.5 \times 10^{-12}$ ergs cm^{-2} s^{-1} in the observed frame and corrected for the Galactic absorption ($N_H^G = 1.45\ 10^{21}$ cm^{-2}, (Dickey & Lockman 1990). 2MASX J0324+3410 has been monitored by the All Sky Monitor (ASM) on-board Rossi X-ray Timing Explorer (RXTE) since June 1996. The average ASM count rate over the last ten years is 0.0343 ± 0.0065 cts s $^{-1}$, converting to a 2–10 keV flux of $F_X = 9.0 \times 10^{-12}$ ergs cm^{-2} s^{-1}. The most recent X-ray observation was done by the Swift X-ray Telescope (XRT) in July 2006. The spectrum in the 0.3-10 keV band can be well fitted with a power-law of a photon index 2.02 ± 0.06 with Galactic absorption. X-ray flux variations up to a factor of two on time-scales less than 1 ks have been detected in the Swift data. The average flux in the 0.2–2.4 keV band was 3 times brighter than that measured in the RASS. Detailed analysis of the X-ray data-sets will be presented in a future paper (Yuan W. et al. in preparation). Of particular interest, a TeV flare was claimed to be marginally detected at a significance level of $\sim 2.5-3.3\,\sigma$ on October 10, 2001 with the Whipple imaging air Cerenkov telescope at the Whipple Observatory (Falcone et al. 2004). The average γ-ray count rate was 0.46 ± 0.14 times that of the Crab, with a peak rate 0.62 ± 0.19 Crab.

The broad band spectral energy distribution (SED) for the nucleus of 2MASX J0324+3410 is plotted in Figure 2, using the results of our own data as well as data collected through the HEASARC web browser. For comparison, the SED for IZw 1 and Mrk 421—a well known NLS1 and blazar, respectively–are over-plotted. It can be seen that 2MASX J0324+3410 resembles Mrk 421 in terms of the broad band, non-thermal continuum in the radio and possibly X-ray bands, whereas it resembles IZw 1 in the infrared–optical regime where thermal emission is dominant.

2.3. The host galaxy — a one-armed spiral?

Two snapshot images of 2MASX J0324+3410, each of 200 s exposure, were taken with the second Wide Field and Planetary Camera (HST/WFPC2) of the Hubble Space Telescope (HST) with the F702W filter (λ_{eff} = 6919 $\AA$). The data were retrieved from the HST archive. The two exposures were combined to create a single image with a better S/N ratio. A ring-like structure of $\sim 15''$ diameter can be clearly seen, which corresponds to ~ 15.6 kpc at redshift 0.0629. A nuclear source with high surface brightness is apparently displaced from the symmetric center of the host galaxy. Thanks to the superb spatial resolution of $\lesssim 0''.1$ of HST, we were able to extract the surface brightness profile of the galaxy and decompose it into two components: an unresolved point-like source as the NLS1 nucleus, and a Sérsic model for the host galaxy (detailed analysis is to be presented in a later paper). We find $m_{NLS1,F702}$ = 15.15 mag for the active nucleus, and $m_{bulge,F702}$ = 15.22 mag for the host galaxy. After correcting for the Galactic extinction E(B-V)=0.213 Mag we get $m_{NLS1,F702} \approx 14.70$ mag. The residual looks like a one-armed spiral (see Fig 1b).

3. Discussion: a NLS1–blazar composite

The spectral and temporal properties of 2MASX J0324+3410 in the radio and X-ray bands, as presented in Sect. 2.2, are characteristic of blazars: a flat radio spectrum and flux variability, a compact and bright radio core on milli-arcsec scale, hard X-ray emission and flares, short timescale variations in X-rays, and a broad band, non-thermal continuum. In particular, its SED and possible TeV γ-ray emission resemble those of a high-energy peaked blazar (HBL). On the other hand, its optical properties fulfill all criteria for classification as NLS1. These observational facts thus make 2MASX J0324+3410 a composite of a NLS1 and a blazar. We note that the rest frame Hβ equivalent width $EW(H\beta) = 58 \pm 4$Å is only slightly below the median value ($\simeq 80$ $\mathring{A}$) for a large sample of NLS1s (Zhou et al. 2006), i.e. the contribution from a potential non-thermal continuum is small in the optical. If the X-ray to optical spectral slope is similar to that of I ZW 1 for the NLS1 component, the NLS1 accounts for only ∼1/3 of the observed X-ray emission, which also has a flat spectrum compared with other NLS1s. Its radio and most likely X-ray radiation can be naturally explained as being from a jet (via synchrotron emission), while the infrared and optical light is dominated by thermal emission from a Seyfert nucleus.

We estimate the central black hole (BH) mass using a few methods. Using the width and luminosity of the Hβ line and the empirical scaling relations as in Greene & Ho (2005), we find a BH mass of $10^7 M_\odot$. While the empirical relations of Vestergaard & Peterson (2006) give BH masses of $3 \times 10^7 M_\odot$ using the continuum luminosity at 5100Åand $1.8 \times 10^7 M_\odot$ using the Hβ luminosity. These BH mass estimates[2] are consistent within their uncertainties, giving $M_{BH} \sim 10^7$ $M_\odot$. Interestingly, this value falls into the overlapping region in the BH mass distributions for NLS1s and blazars, which have the bulk lying within 10^{6-7} $M_\odot$ (e.g., Wang & Lu 2001; Grupe & Mathur 2004; Zhou et al. 2006) and 10^{7-9} $M_\odot$ (e.g., Woo et al. 2005, Falomo et al. 2002), respectively.

We estimate the bolometric luminosity from the 5100Åluminosity using the correction factor for quasars given by Elvis et al. (1994). This gives $L_{\rm bol} \approx 1.2\ 10^{45}$ $erg\ s^{-1}$. We thus obtain a rough estimate of the Eddington ratio $\dot{m} \equiv L_{\rm bol}/L_{\rm Edd} \approx 0.1$ for 2MASX J0324+3410. The Eddington ratio is typical of NLS1s, and resembles FSRQ as far as its blazar property is concerned; however, the SED of its jet emission is more like HBLs, which have, on the contrary, generally low accretion rates. The one-armed spiral may provide such fueling to the active nucleus, though it cannot be completely ruled out that the HST image we see is a structure made up by dust lanes or even a ring galaxy.

2MASX J0324+3410 is not unique, but is the most representative object of its kind, which seem to be rare. The optical spectrum of the BL Lac object 0846+51W1 showed typical NLS1 characteristics at low states (Zhou et al. 2005). The radio-to-optical SED

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[2] We note that a higher black hole mass of $8 \times 10^7 M_\odot$ is estimated if one uses the line dispersion instead of the *FWHM*, following Collin et al. (2006).

of the radio loud NLS1 J094857.3+002225, for which beaming is required to explain the high brightness temperature, is also similar to that of 2MASX J0324+3410 (Zhou et al. 2004; also Doi et al. 2006). A third example is RXJ 16290+4007 (Zhou & Wang 2002; also Komossa et al. 2006b), a flat-spectrum radio quasar with NLS1 characteristics in the optical. Furthermore, 8 out of the 9 very-radio-loud (VRL, $R_{1.4} \equiv f_{1.4GHz}/f_B \gtrsim 250$) NLS1s currently under study (Zhou et al. 2006b in preparation) show flat radio spectra: [3], $\alpha_{1.4-5GHz} \lesssim 0.5$, $f_\nu \propto \nu^{-\alpha}$, which is remarkable. Thus, it is probably true that most VRL NLS1s are actually radio intermediate (RI) NLS1s with boosted jet emission (Zhou et al. 2006b). If so, they are similar to a population of boosted RI quasars recently identified by Wang et al (2006) from their high radio brightness temperature, but with more extreme optical properties. They may be an analog to the radio-bright, very high soft states in black hole binaries (e.g., Fender, Belloni & Gallo 2004).

The hybrid state of 2MASX J0324+3410 raises questions to the current understanding of TeV/high-energy peaked blazars. It is widely accepted that this type of blazar have very low accretion rates, but 2MASX J0324+3410 is doubtlessly an exception. A common notion is that the intensive radiation field of the accretion disk prevents electrons from gaining the high energies that are required for TeV γ-ray production or the formation of high frequency synchrotron peaks in the SED. This is certainly not the case for 2MASX J0324+3410.

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[3] the only exception so far is SDSS J172206.03+565451.6 with $\alpha_{0.33-1.4GHz} = 0.7$ (Komossa et al. 2006b).

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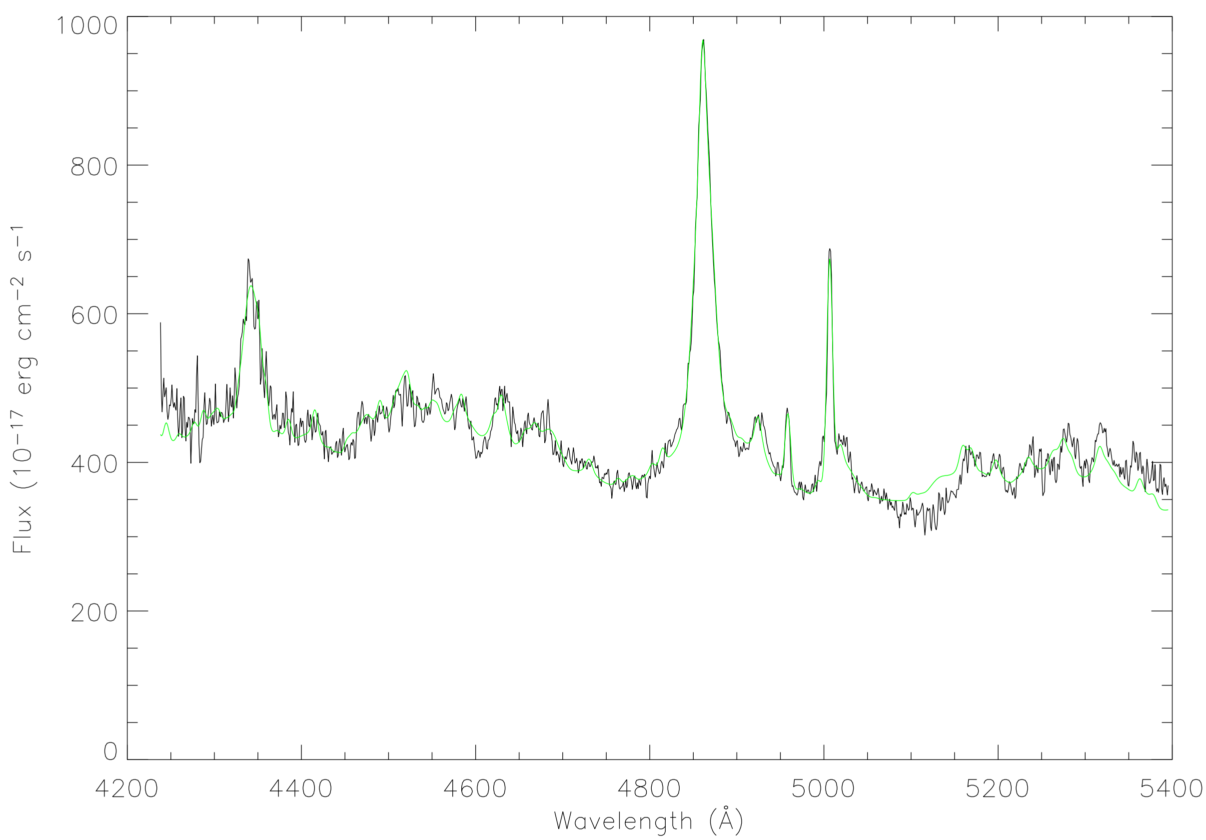

Fig. 1.— Observed spectrum of 2MASX J0324+3410 and the best fit model (the green line).

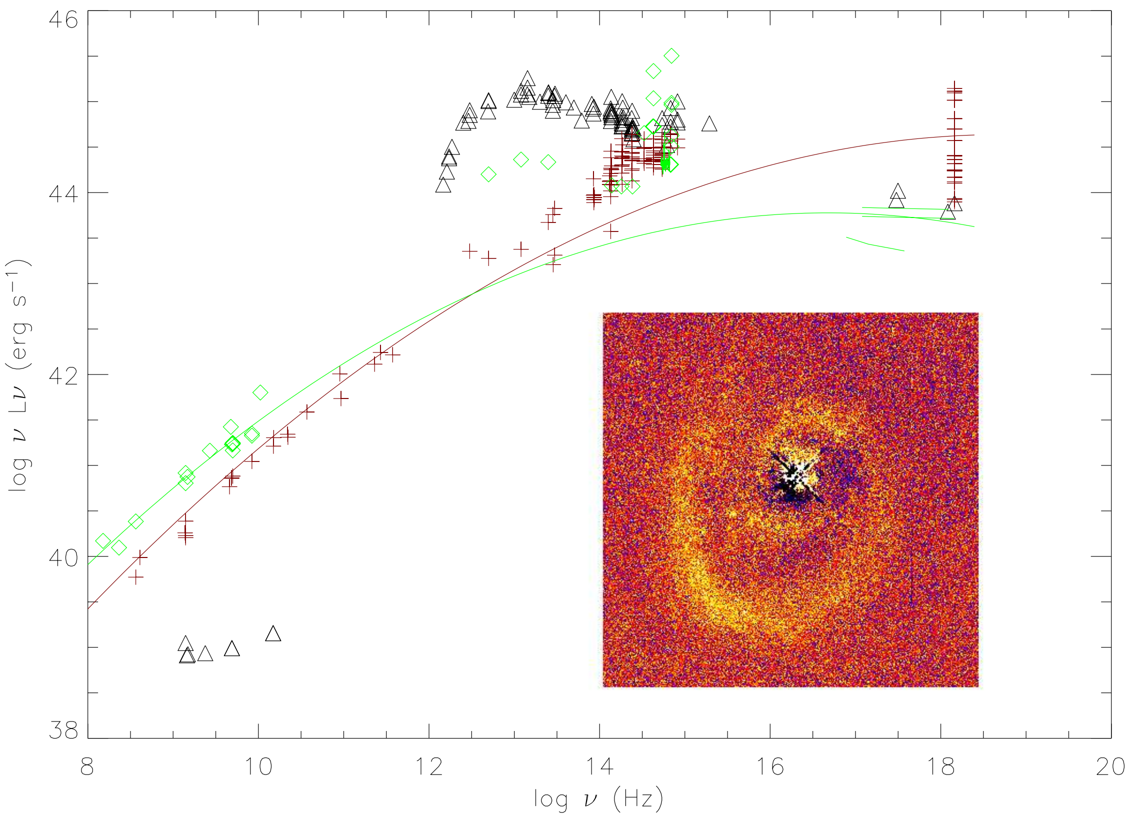

Fig. 2.— Broad-band spectral energy distribution of 2MASX J0324+3410 (green diamonds)